



Results from the Daya Bay Reactor Neutrino Experiment



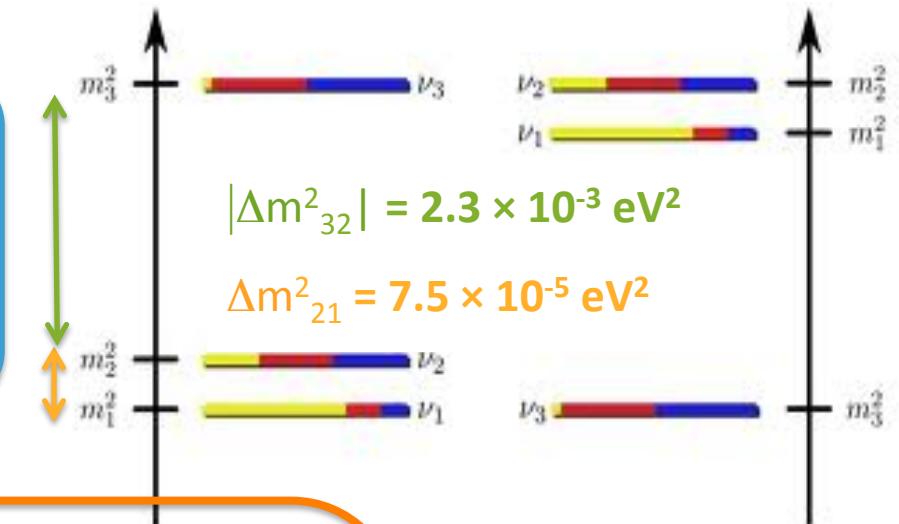
Elizabeth Worcester (BNL) on behalf of the Daya Bay Collaboration
SSP 2015, Victoria, BC
June 12, 2015



3 Neutrino Model



- $|\nu_i\rangle = \sum_{\alpha} U_{\alpha i}^* |\nu_{\alpha}\rangle$
- Flavor composition of neutrinos change as they propagate



$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}} \sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}} \sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

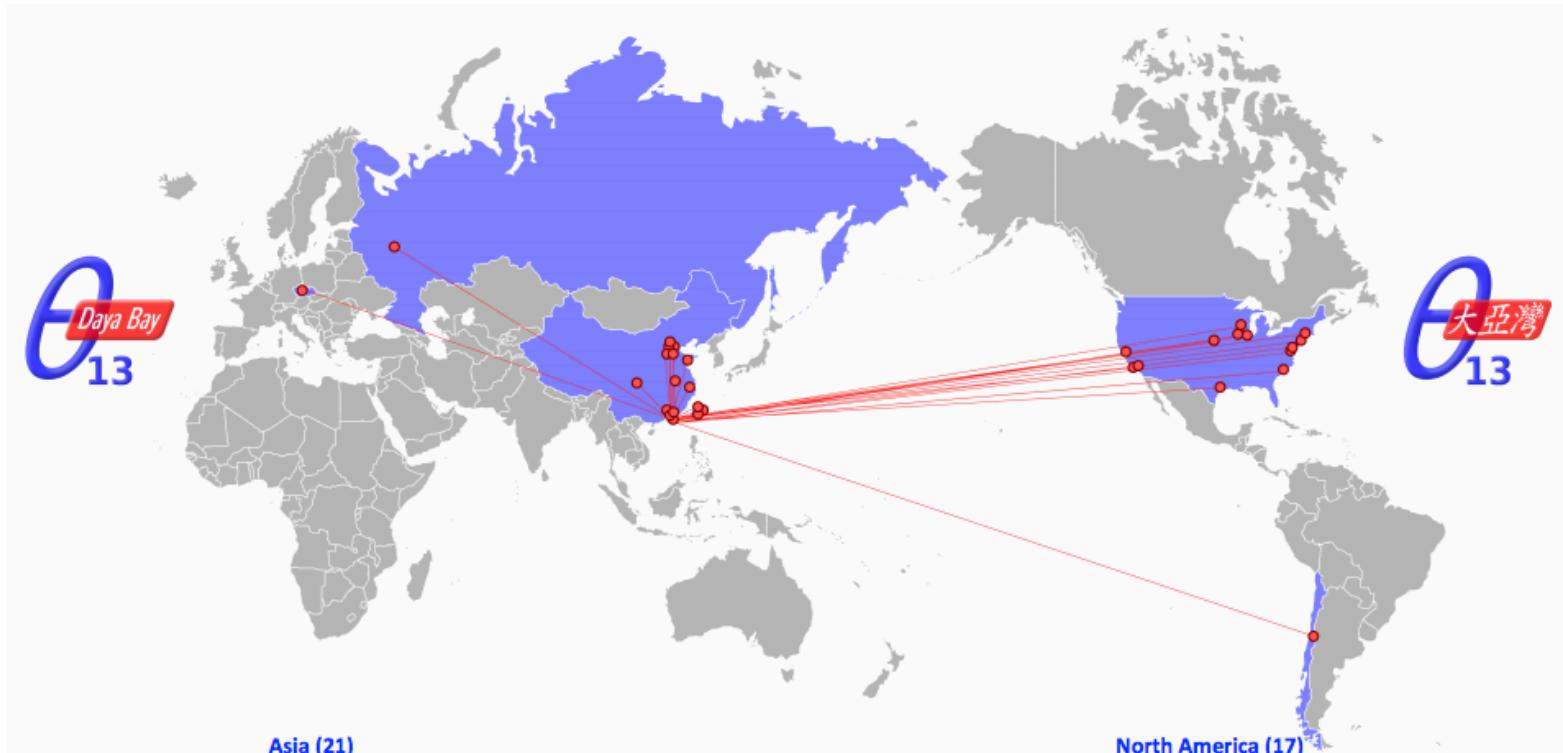
• $\theta_{23} \approx 45^\circ$
 • Atmospheric, Accelerator
 • Octant unknown

• $\theta_{13} \approx 10^\circ$
 • Short-Baseline Reactor, Accelerator
 • δ_{CP} unknown

• $\theta_{12} \approx 35^\circ$
 • Solar, Long-Baseline Reactor



Daya Bay Collaboration



Asia (21)

Beijing Normal Univ., CGNPG, CIAE, Dongguan Polytechnic, ECUST, IHEP, Nanjing Univ., Nankai Univ., NCEPU, Shandong Univ., Shanghai Jiao Tong Univ., Shenzhen Univ., Tsinghua Univ., USTC, Xian Jiaotong Univ., Zhongshan Univ., Chinese Univ. of Hong Kong, Univ. of Hong Kong, National Chiao Tung Univ., National Taiwan Univ., National United Univ.

North America (17)

Brookhaven Natl Lab, CalTech, Illinois Institute of Technology, Iowa State, Lawrence Berkeley Natl Lab, Princeton, Siena College, Temple University, UC Berkeley, UCLA, Univ. of Cincinnati, Univ. of Houston, UIUC, Univ. of Wisconsin, Virginia Tech, William & Mary, Yale

Europe (2)

Charles University, JINR Dubna

South America (1)

Catholic Univ. of Chile

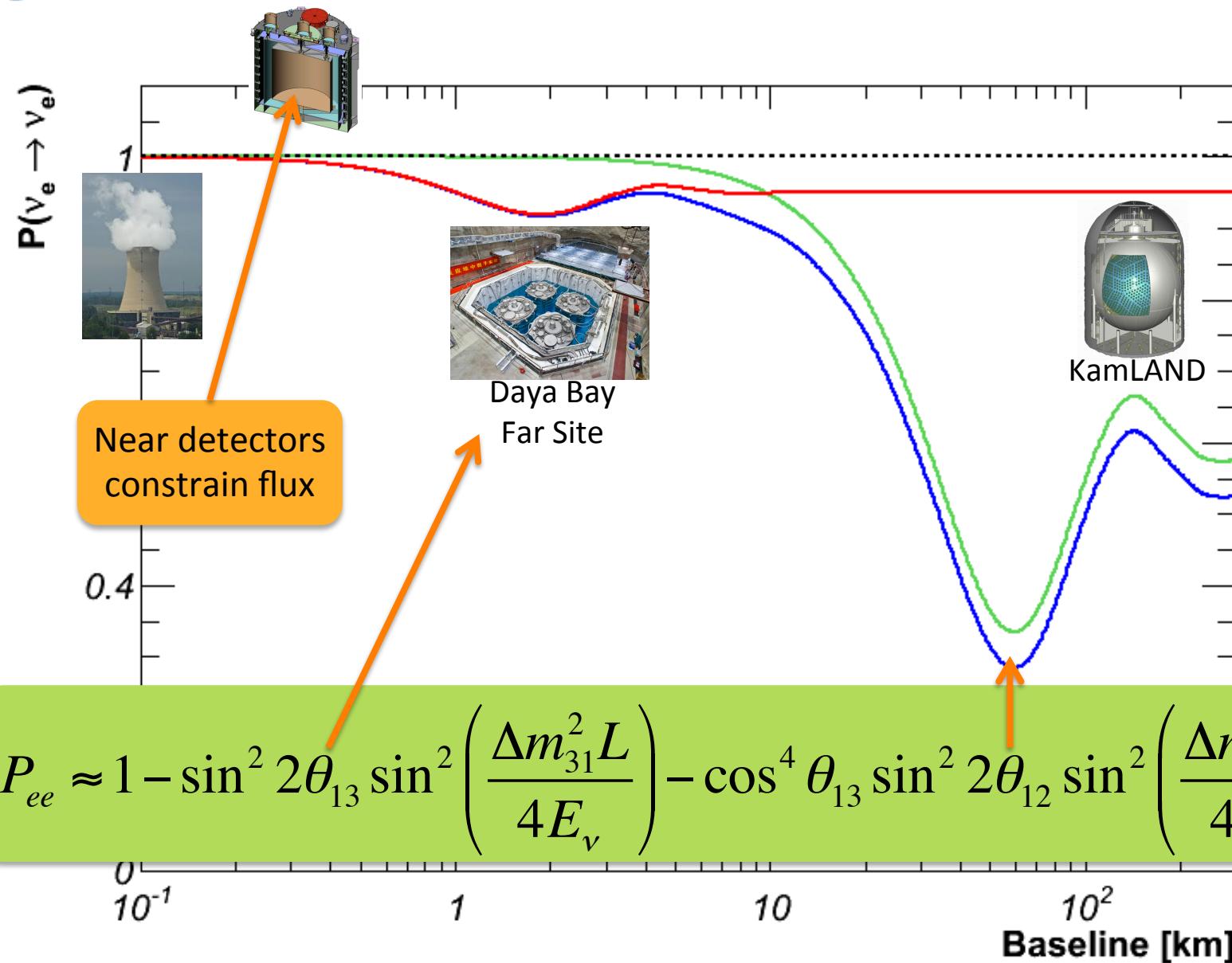


Daya Bay Collaboration





Reactor Neutrino Oscillation





Site: Guangdong, China



Entrance to Daya Bay experiment tunnels

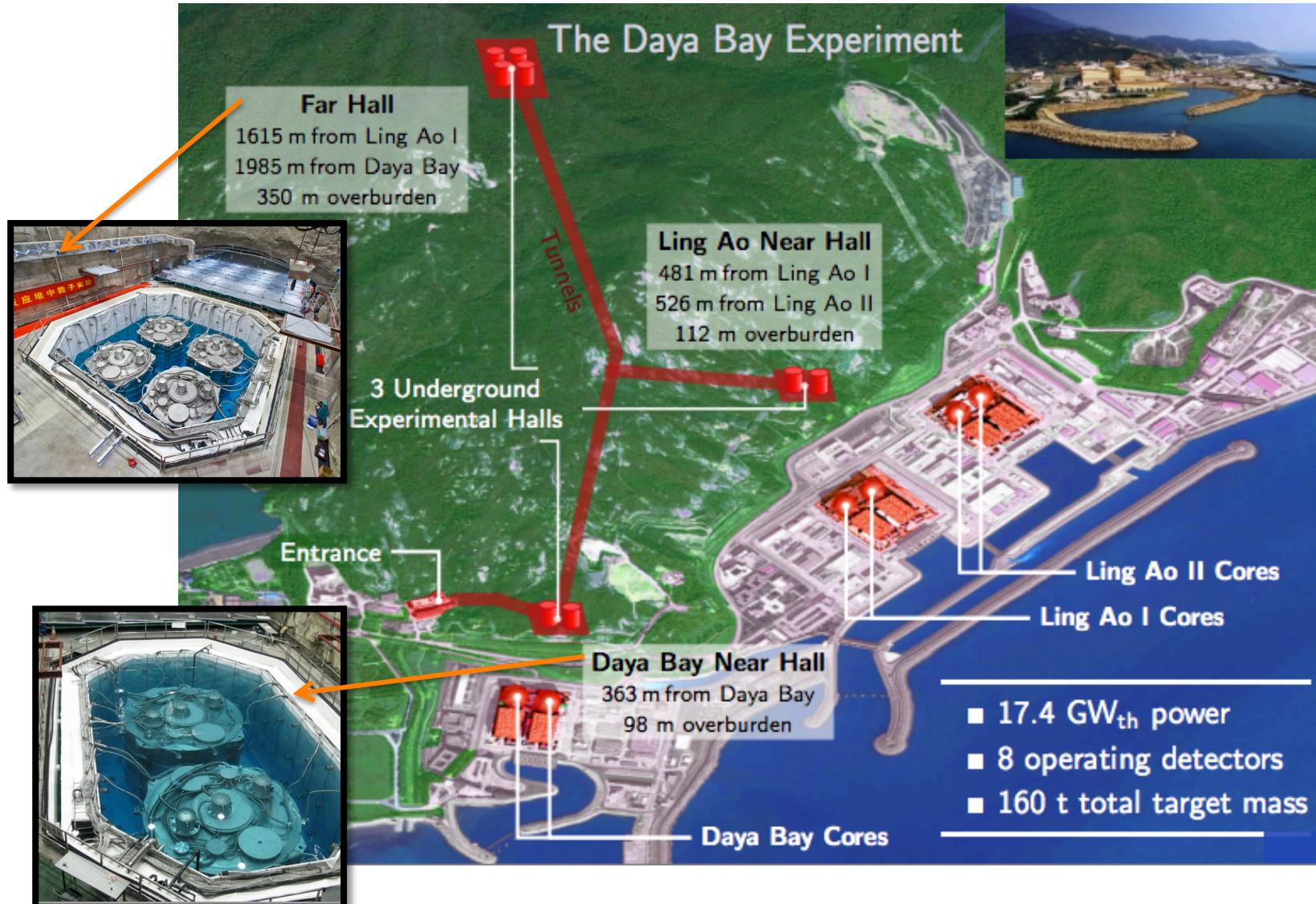
Daya Bay NPP
2.9GW×2

Ling Ao NPP
2.9GW×2

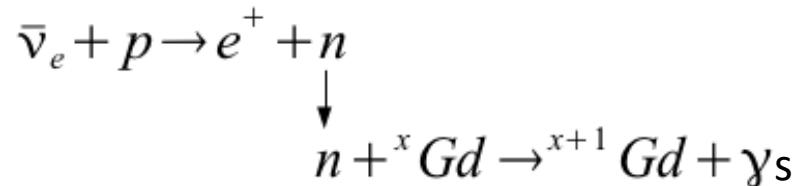
Mountains shield detectors from cosmic-ray induced background



Experiment Layout



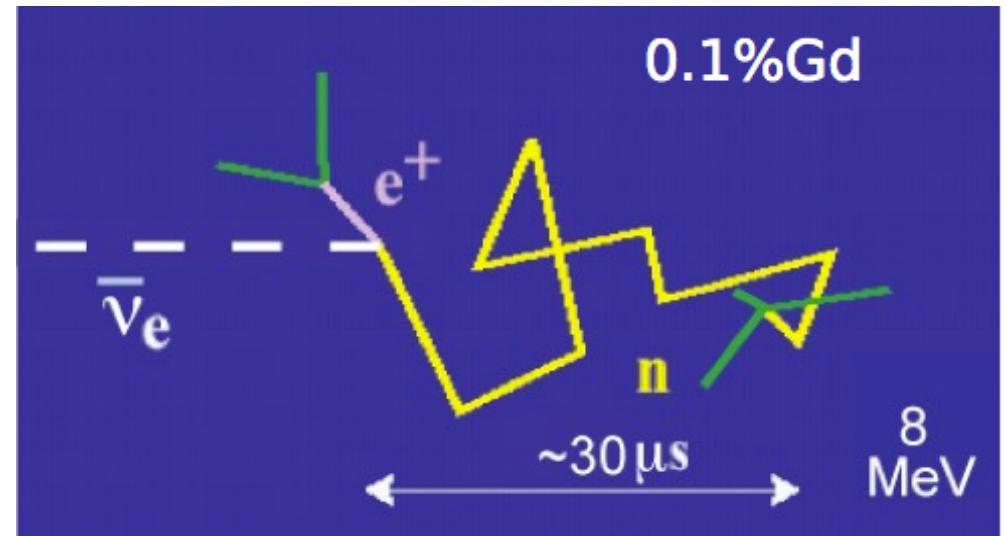
Inverse β -decay (IBD):



Prompt positron:

Carries antineutrino energy

$$E_{e^+} \approx E_\nu - 0.8 \text{ MeV}$$

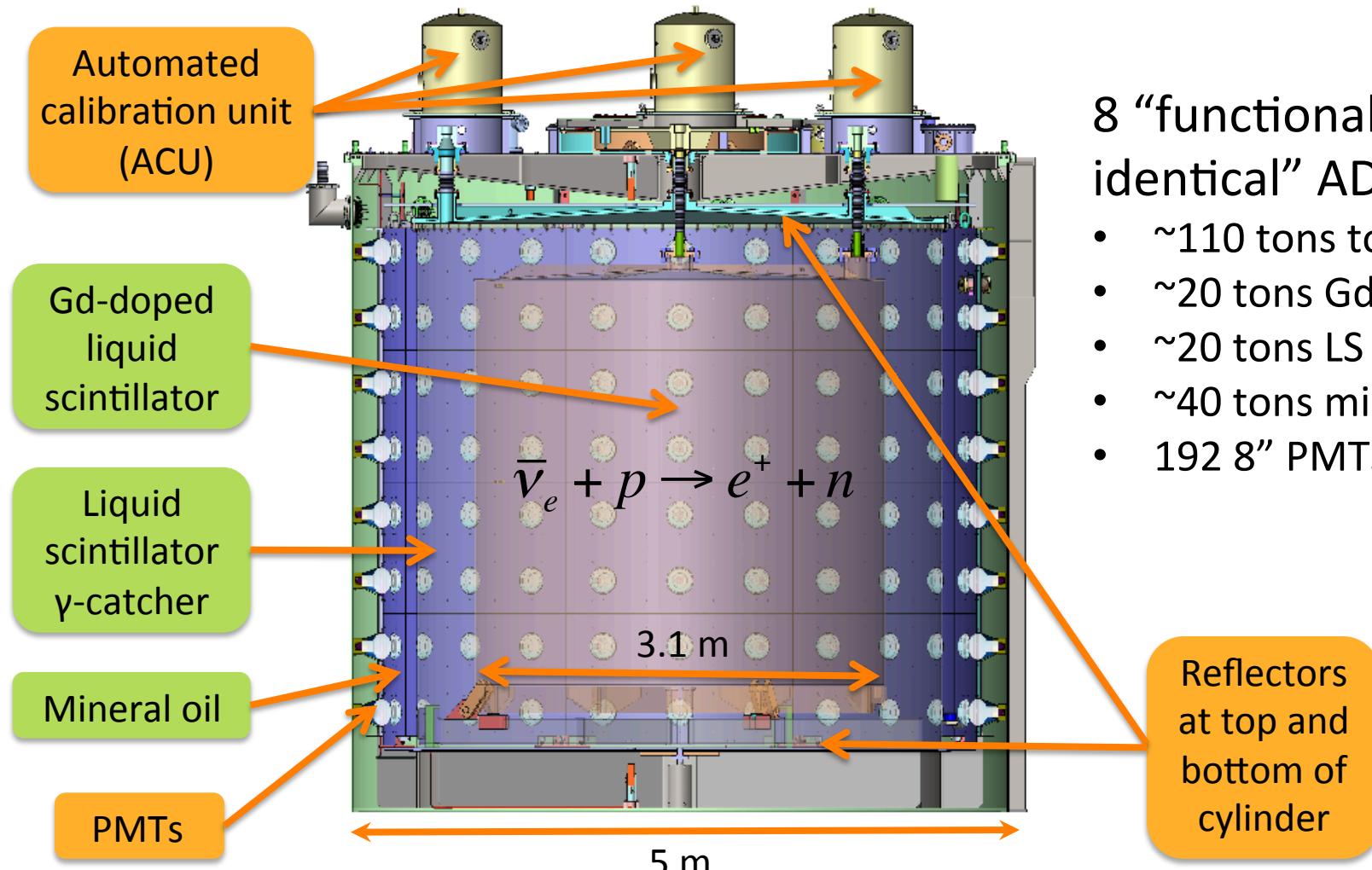


Delayed neutron capture:

Efficiently tags antineutrino signal

Prompt + Delayed coincidence provides distinctive signature

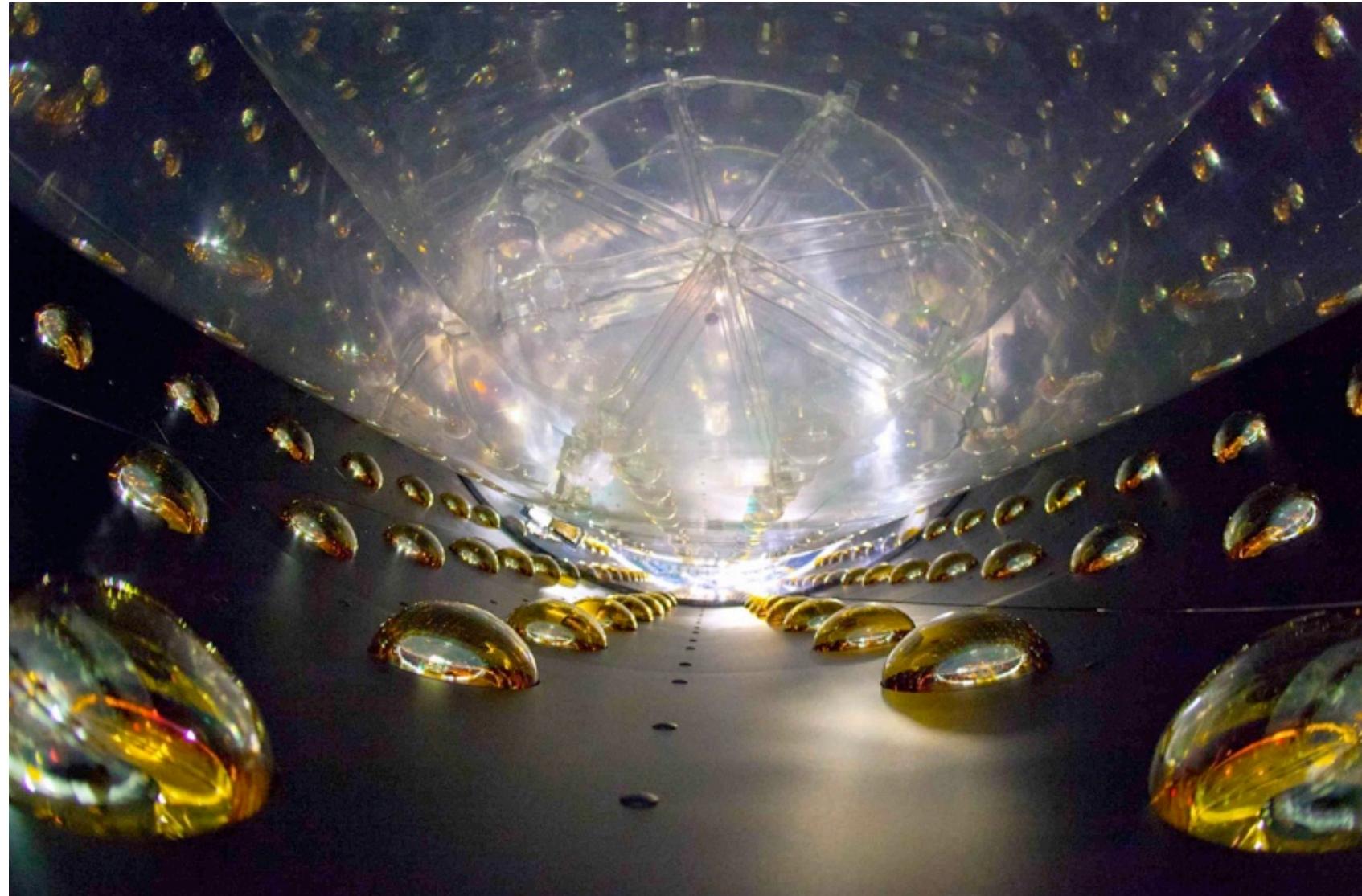
Antineutrino Detectors (ADs)



8 “functionally identical” ADs

- ~110 tons total
- ~20 tons Gd-doped LS
- ~20 tons LS
- ~40 tons mineral oil
- 192 8" PMTs

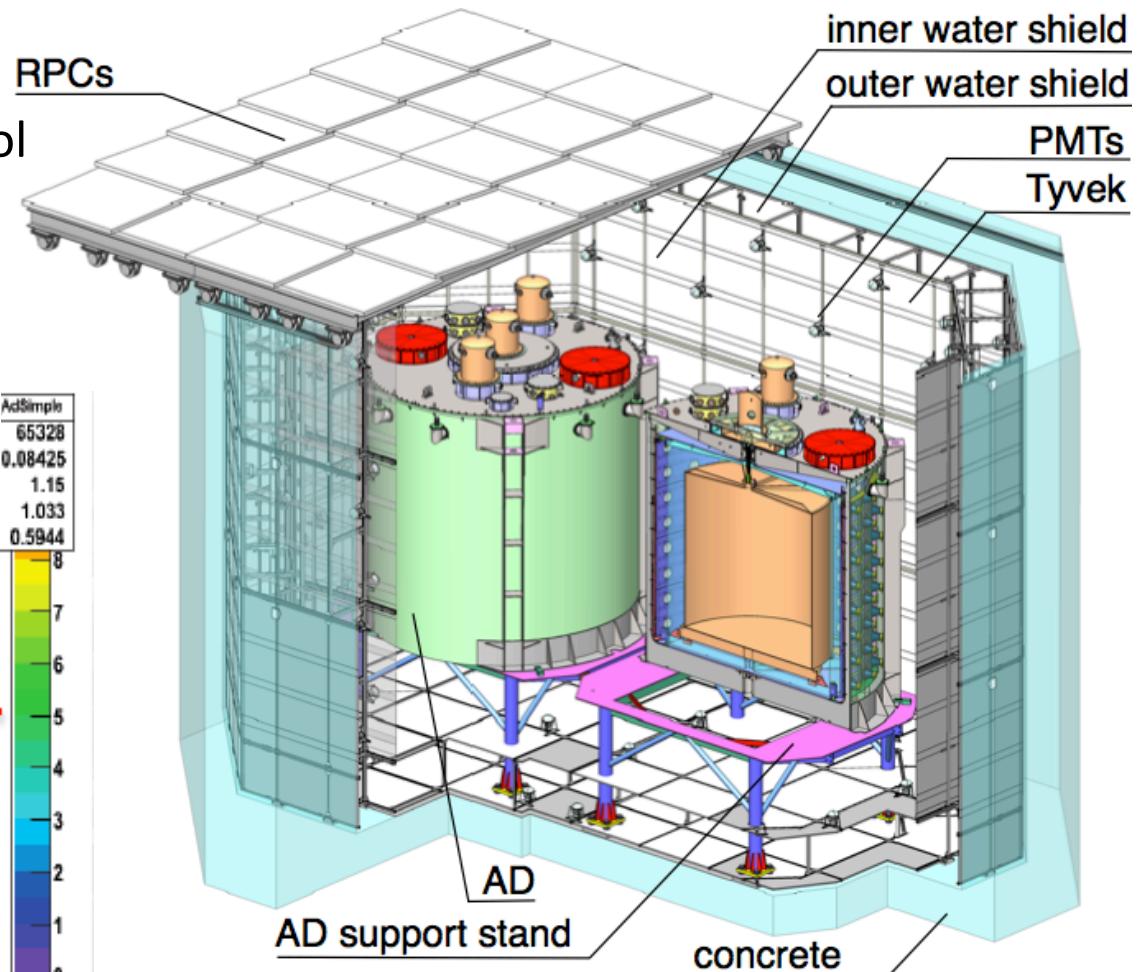
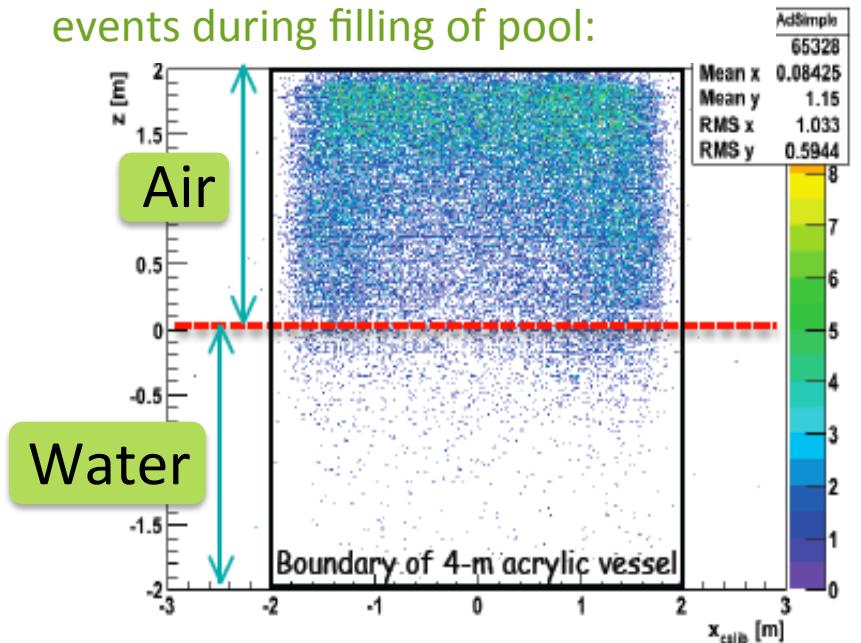
Interior of AD



Muon Tagging System

- Water Pool acts as shield and Cerenkov detector
- 4-layer RPC modules above pool

Passive shielding demonstration:
reconstructed position of AD single events during filling of pool:

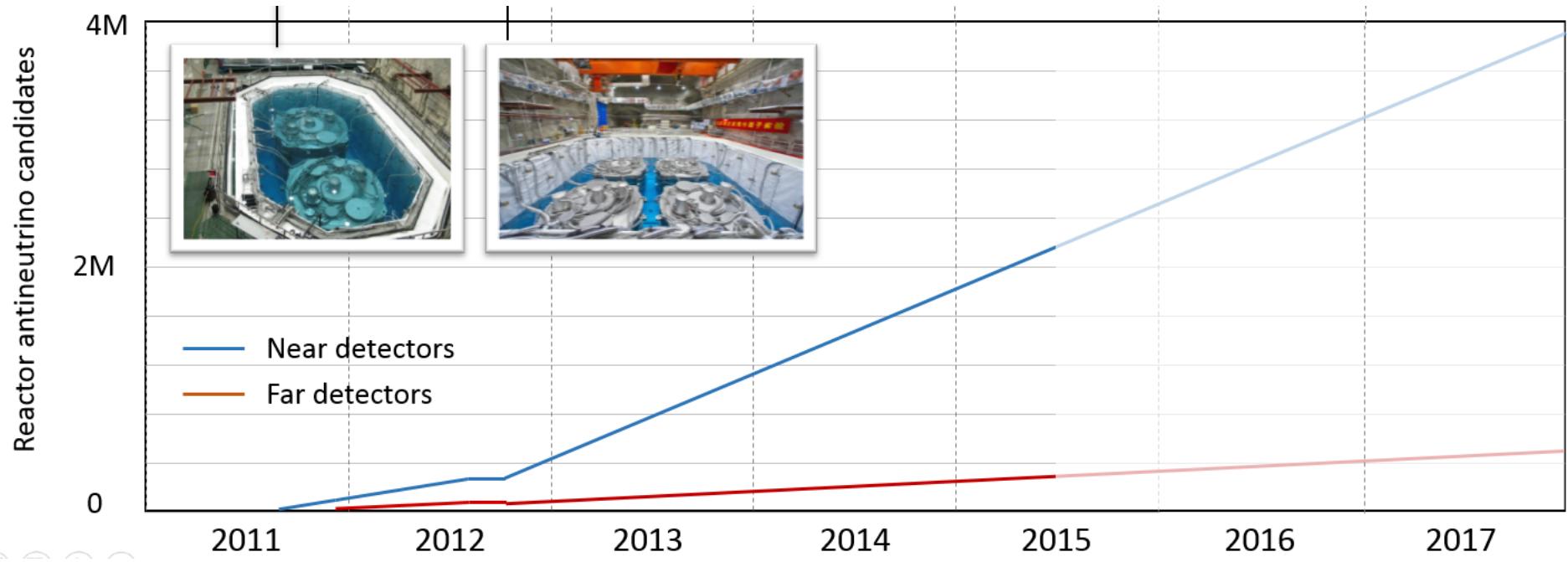




Data Collection



- **6-AD Configuration:**
 - 2 ADs (EH1), 1 AD (EH2), 3 ADs (EH3)
 - December 2011 to July 2012
 - 217 days of data
- **8-AD Configuration:**
 - 2 ADs (EH1), 2 ADs (EH2), 4 ADs (EH3)
 - October 2012 to present
 - Current analysis includes 404 days of data (through November 2013)

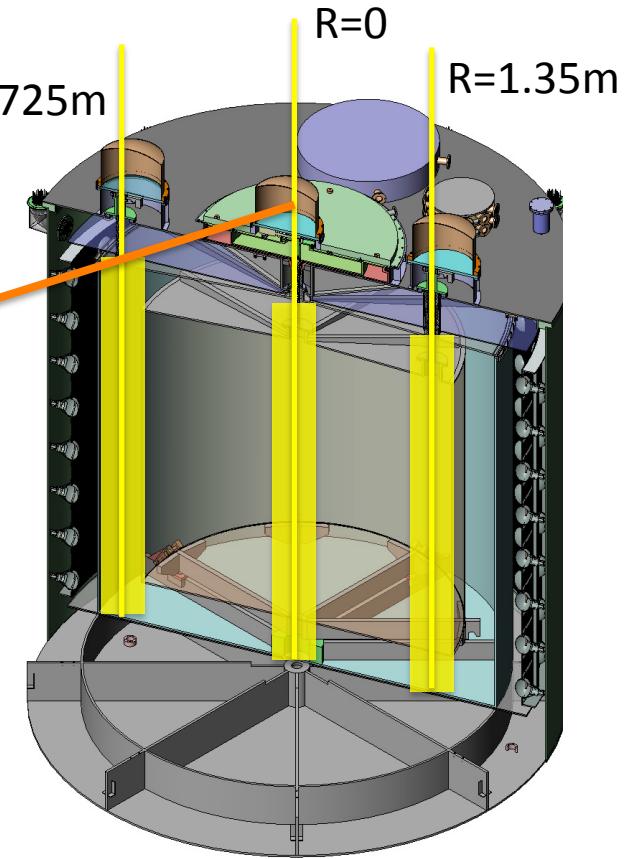
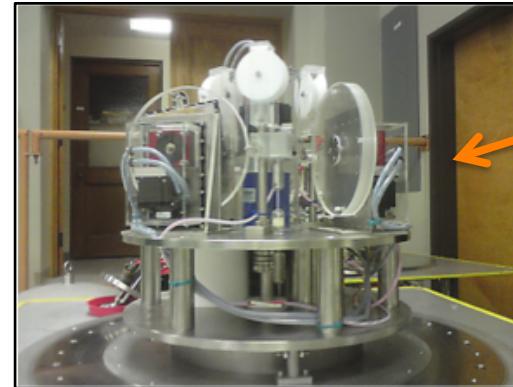


Calibration: ACUs

Each ACU contains 3 sources on turntable:

^{68}Ge source

- 0 KE $e^+ = 2 \times 0.511 \text{ MeV } \gamma$



ACUs deploy sources along 3 axes: center of target, edge of target, center of gamma catcher

$^{241}\text{Am}-^{13}\text{C}$ neutron source

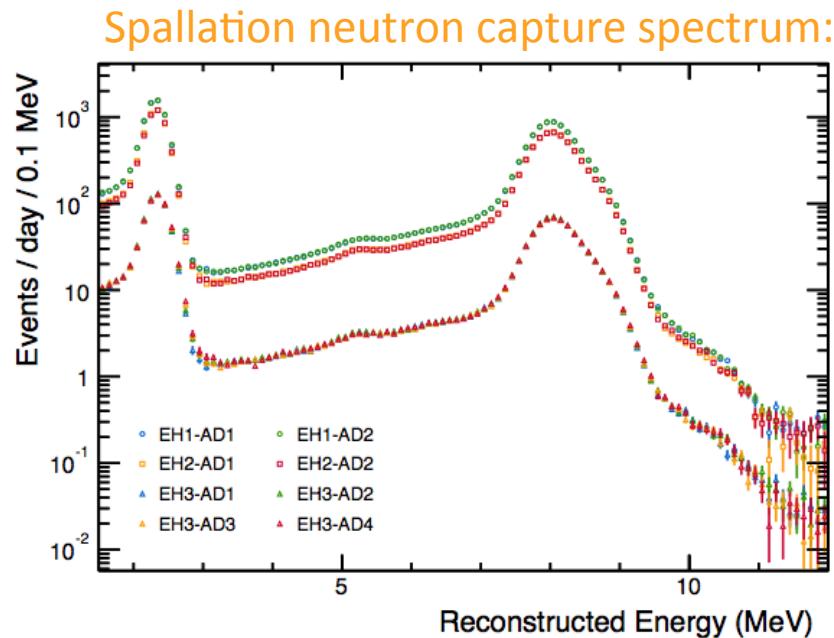
- ~3.5 MeV n without γ
- ^{60}Co gamma source
- 1.173+1.332 MeV γ

LED diffuser ball

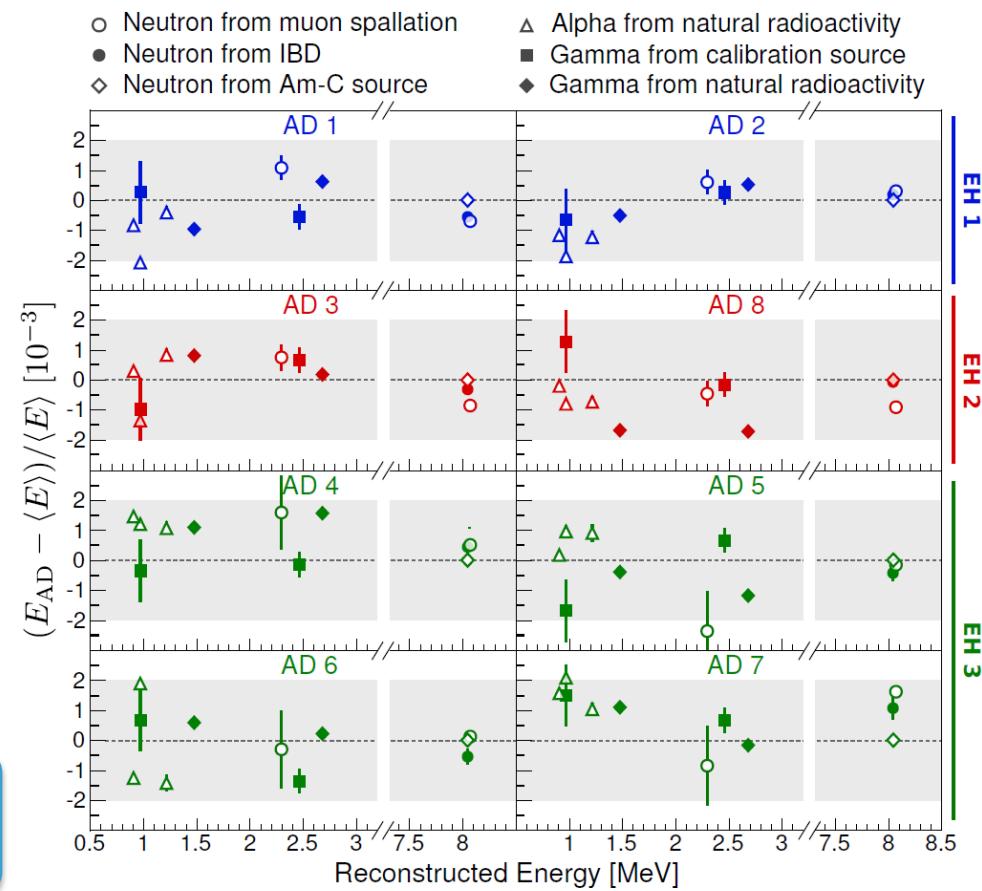
Calibration also makes use of spallation neutron and natural radioactivity data taken simultaneously with IBD data during regular physics data collection.

Side-by-Side Comparison

Detailed comparisons and crosschecks possible with multiple detectors.



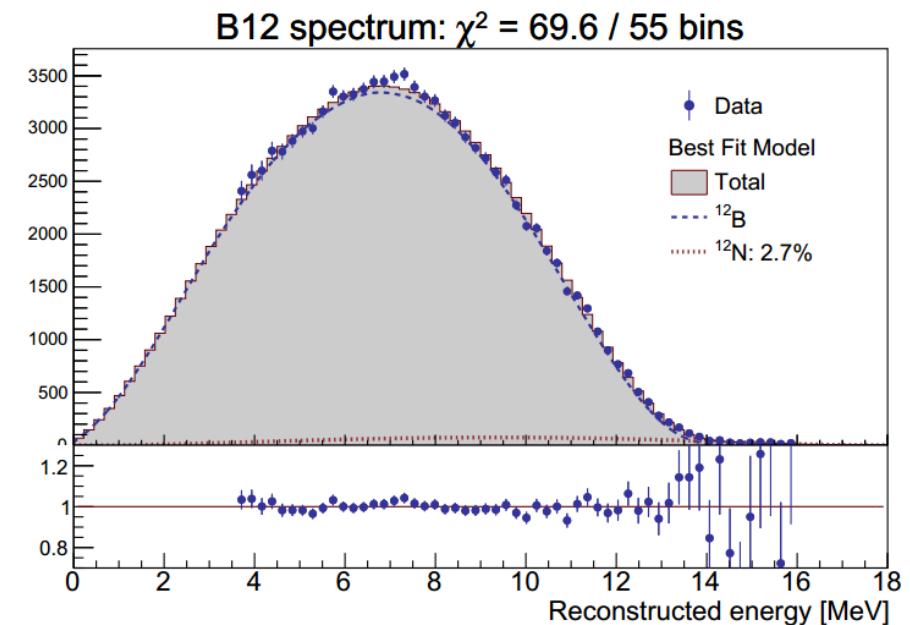
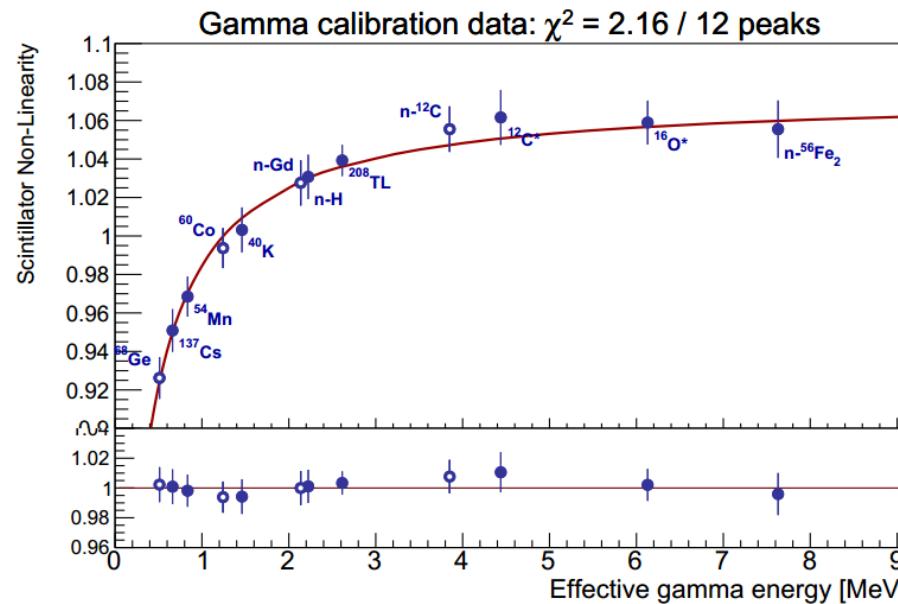
Functionally identical response for side-by-side detectors.



Systematic energy scale variations among all ADs for all calibration methods < 0.2%.

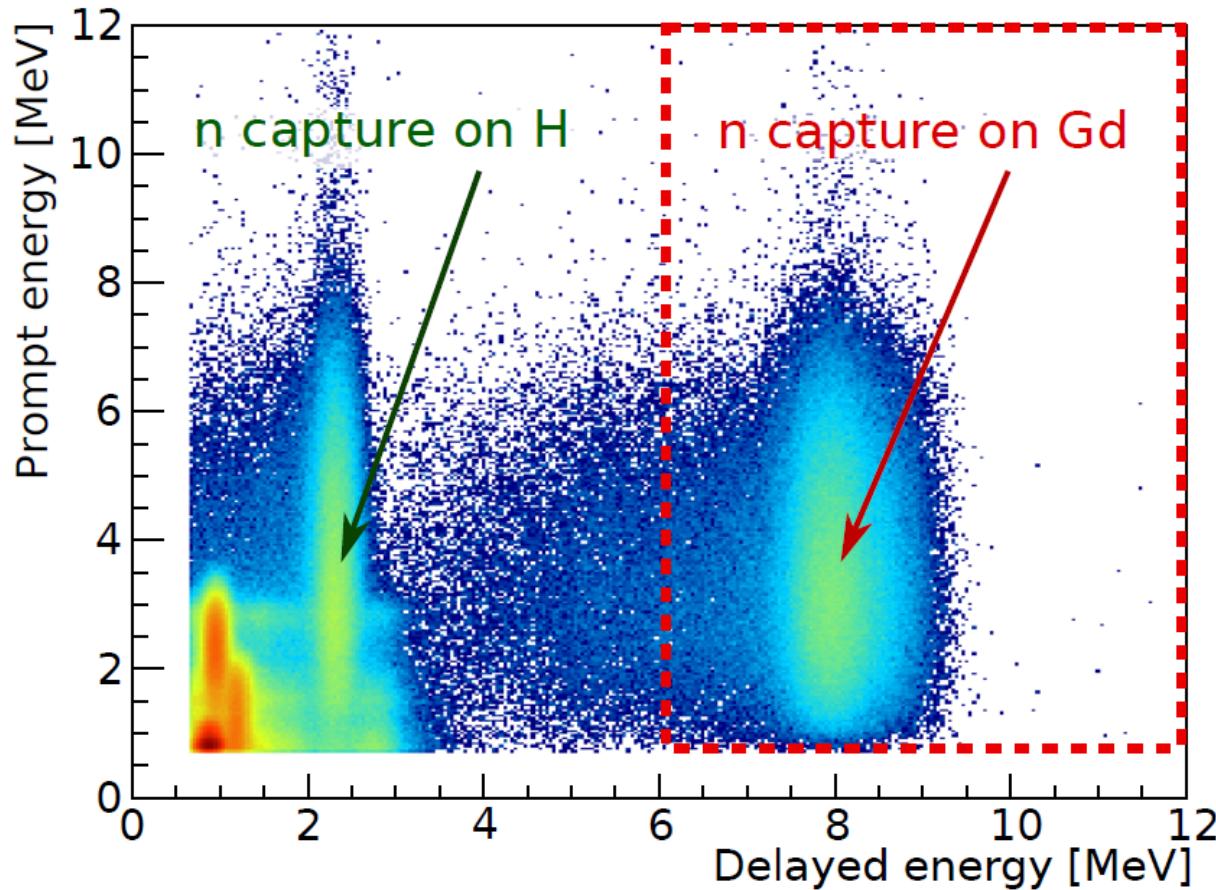


Detector Energy Response



- Sources of detector non-linearity:
 - Scintillator quenching (Birks' Law)
 - Cerenkov light
 - PMT readout electronics response
- Model constrained by fit to mono-energetic gamma peaks and ^{12}B beta-decay spectrum

Correlated IBD Signature



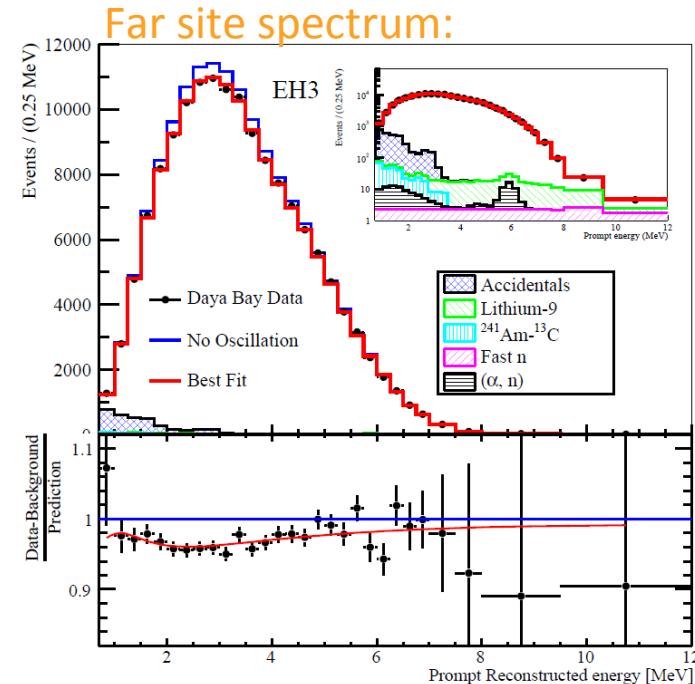
- IBD nGD Selection
 - Reject “flashers”
 - Prompt positron: $0.7 \text{ MeV} < E_p < 12 \text{ MeV}$
 - Delayed neutron: $6.0 \text{ MeV} < E_d < 12 \text{ MeV}$
 - Capture Time: $1 \mu\text{s} < \Delta t < 200 \mu\text{s}$
- Muon Veto
 - Pool muon: veto following 0.6 ms
 - AD muon ($> 20 \text{ MeV}$): veto following 1 ms
 - AD shower muon ($> 2.5 \text{ GeV}$): veto following 1 s
- Multiplicity
 - No other signal $> 0.7 \text{ MeV}$ within $\pm 200 \mu\text{s}$ of IBD

Clear separation of antineutrino IBD events from most other signals

Background

Low background experiment:

- 3% at far site
- 2% at near sites



Background	Near	Far	Uncertainty	Method
Accidentals	1.4%	2.3%	Negligible	Statistically calculated from uncorrelated singles
$^9\text{Li}/^8\text{He}$	0.4%	0.4%	~50%	Measured with after-muon events
Fast neutron	0.1%	0.1%	~30%	Measured from tagged muon events
AmC source	0.03%	0.2%	~50%	MC benchmarked with single gamma and strong AmC source; some sources removed from far site for 8-AD period
Alpha-n	0.01%	0.1%	~50%	Calculated from measured radioactivity



Data Summary (“6+8 AD” Data)



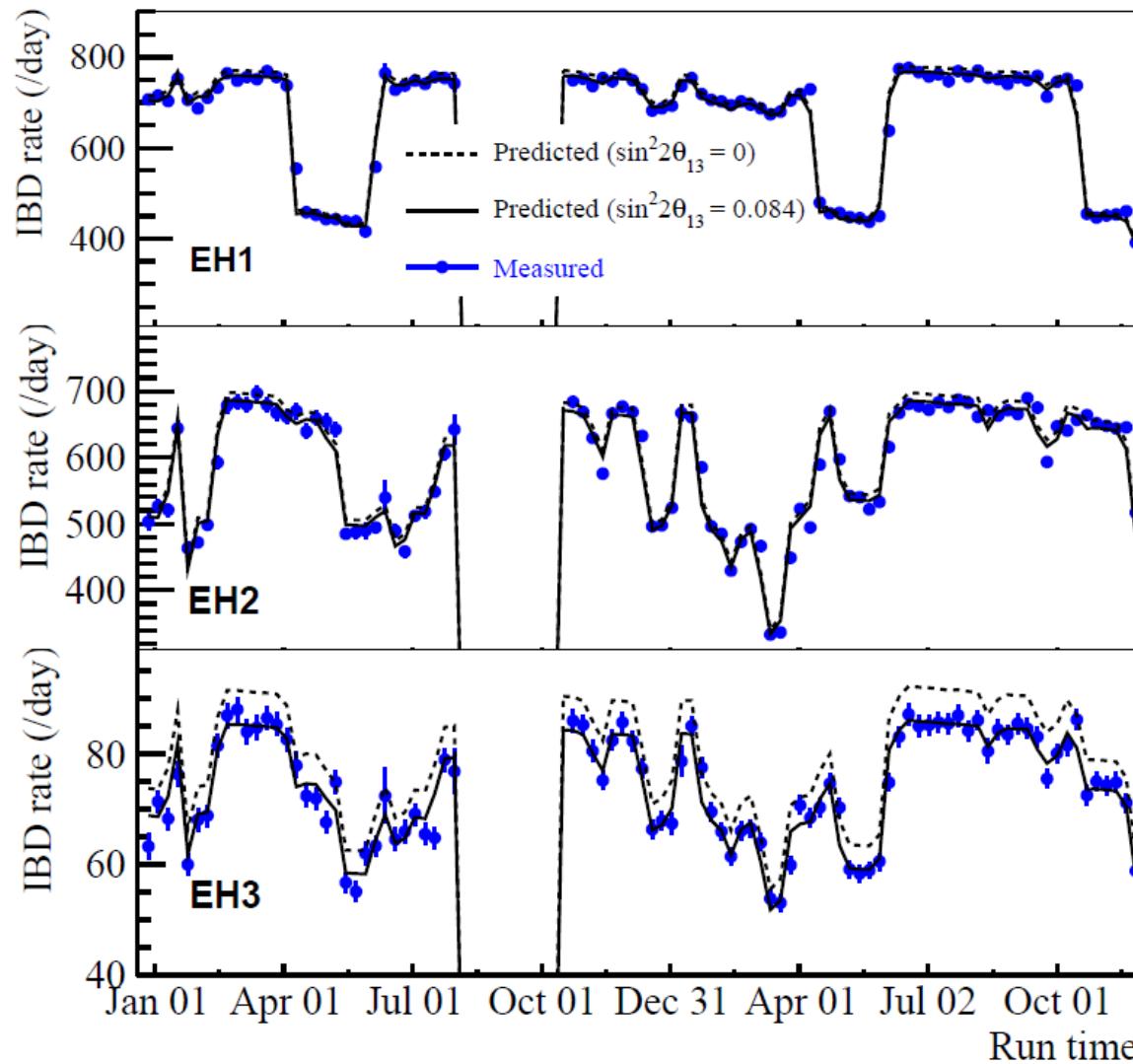
	EH1		EH2		EH3			
	AD1	AD2	AD3	AD8*	AD4	AD5	AD6	AD7*
IBD candidates (total)	304459	309354	287098	190046	40956	41203	40677	27419
Live time (days)	565		568	378		562		373
Efficiency Corr. (%)	80.3	80.1	83.7	83.7	95.7	95.7	95.6	95.7
Accidentals (/day)	8.92 ±0.09	8.94 ±0.09	6.76 ±0.07	6.86 ±0.07	1.70 ±0.02	1.59 ±0.02	1.57 ±0.02	1.26 ±0.02
Fast Neutrons (/AD/day)	0.78 ± 0.12		0.54 ± 0.19		0.05 ± 0.01			
⁹ Li/ ⁸ He (/AD/day)	2.8 ± 1.5		1.7 ± 0.9		0.27 ± 0.14			
Am-C corr. 6-AD period (/day)	0.27 ±0.12	0.25 ±0.11	0.27 ±0.12	n/a	0.22 ±0.10	0.21 ±0.10	0.21 ±0.09	n/a
Am-C corr. 8-AD period (/day)	0.20 ±0.09	0.21 ±0.10	0.18 ±0.08	0.22 ±0.10	0.06 ±0.03	0.04 ±0.02	0.04 ±0.02	0.07 ±0.03
¹³ C(α, n) ¹⁶ O (/day)	0.08 ±0.04	0.07 ±0.04	0.05 ±0.03	0.07 ±0.04	0.05 ±0.03	0.05 ±0.03	0.05 ±0.03	0.05 ±0.03
IBD Rate (/day)	657.2 ±1.9	670.1 ±1.9	594.8 ±1.5	590.8 ±1.7	73.9 ±0.41	74.5 ±0.41	73.6 ±0.40	75.2 ±0.49

Systematic Uncertainty

	Efficiency	Correlated Uncertainty	Uncorrelated Uncertainty
Target protons		0.47%	0.03%
Flasher cut	99.98%	0.01%	0.01%
Delayed energy cut	92.7%	0.97%	0.12%
Prompt energy cut	99.81%	0.10%	0.01%
Capture time cut	98.70%	0.12%	0.01%
Gd capture ratio	84.2%	0.95%	0.10%
Spill-in correction	104.9%	1.50%	0.02%
Combined	80.6%	2.1%	0.2%

Only **uncorrelated** uncertainties affect oscillation analyses.

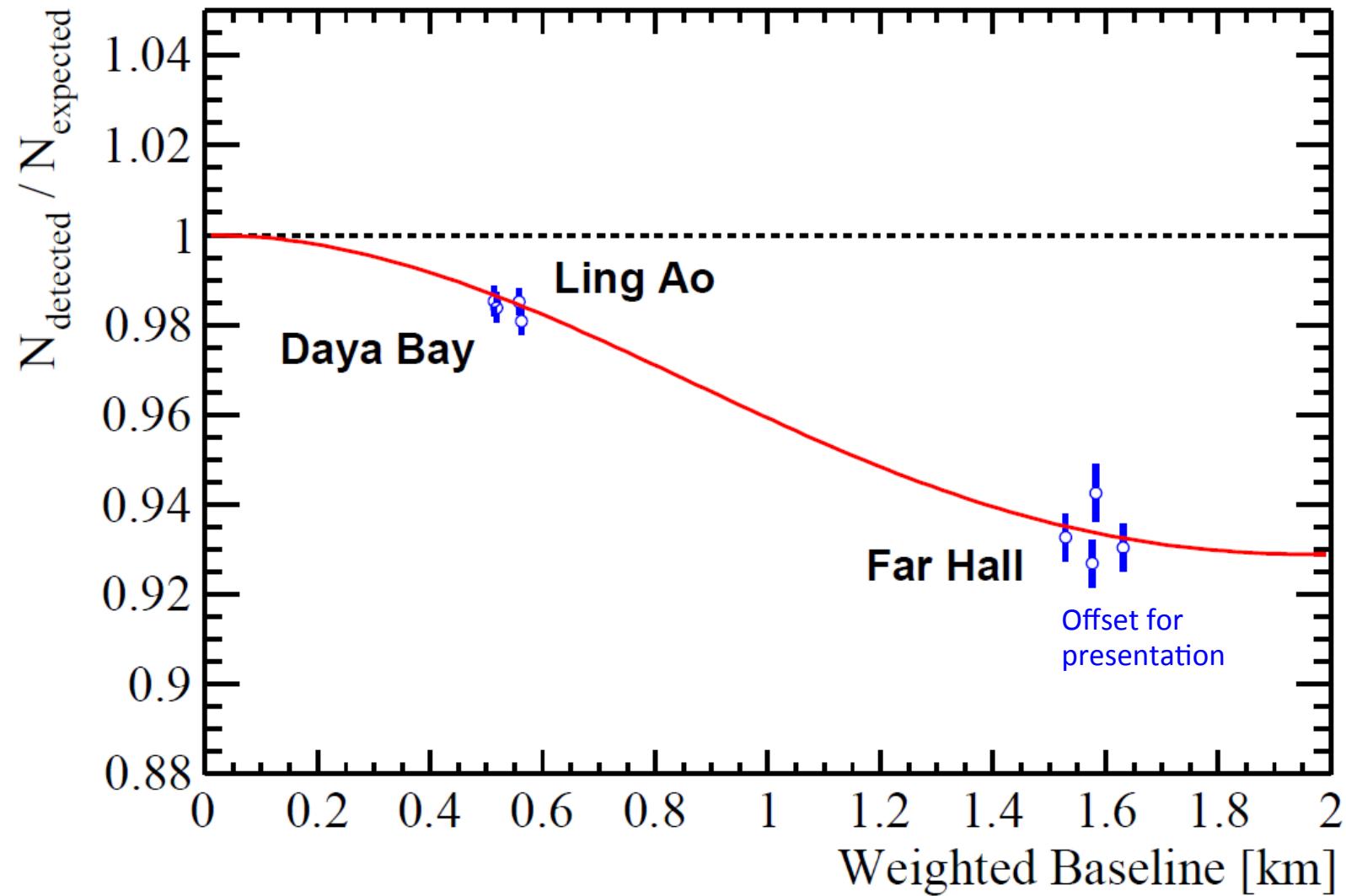
Antineutrino Rate vs. Time



- Detected rate strongly correlated with reactor flux expectations

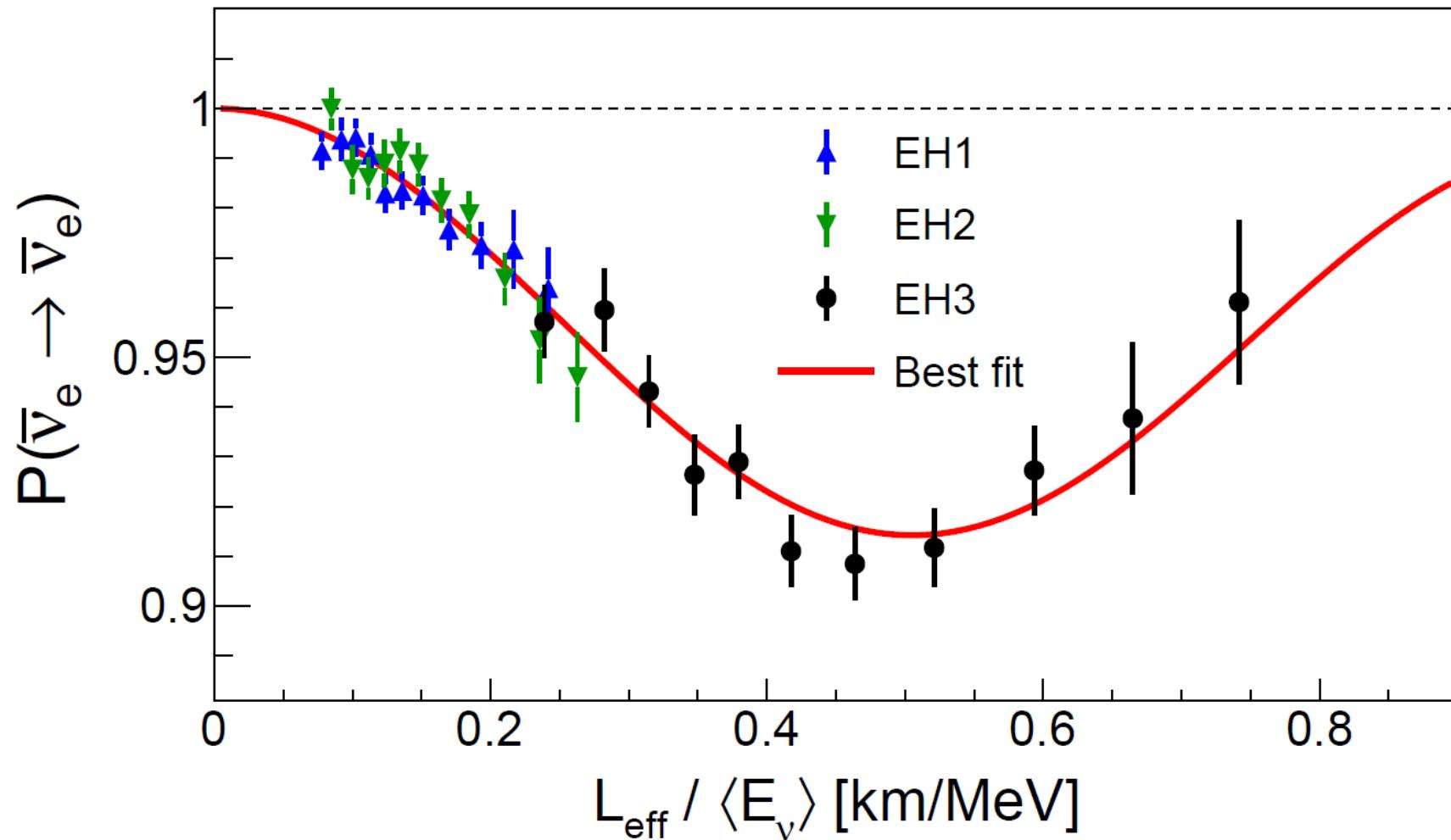


Oscillation Observed



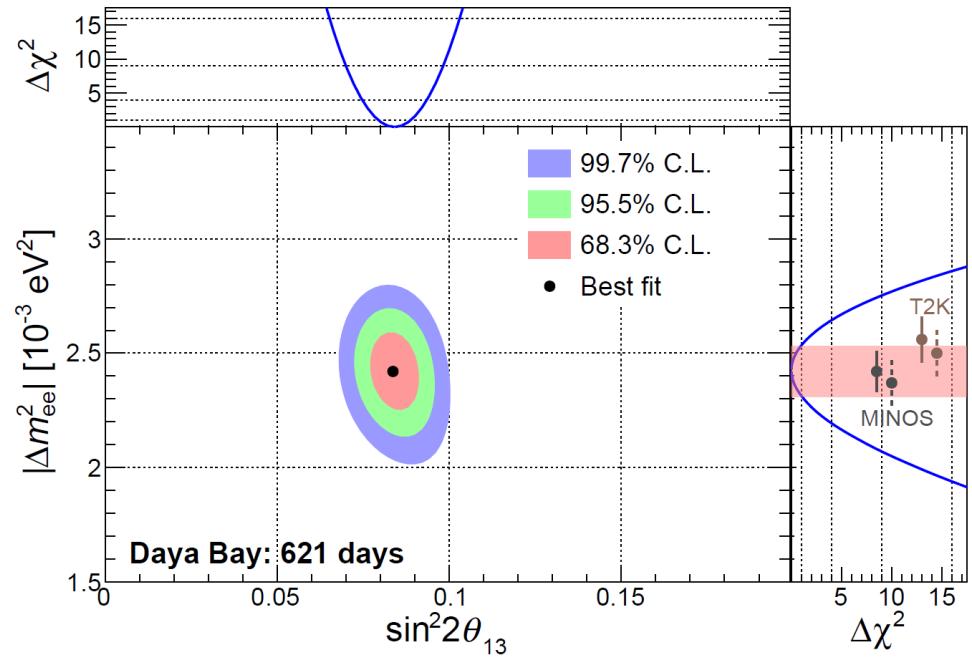
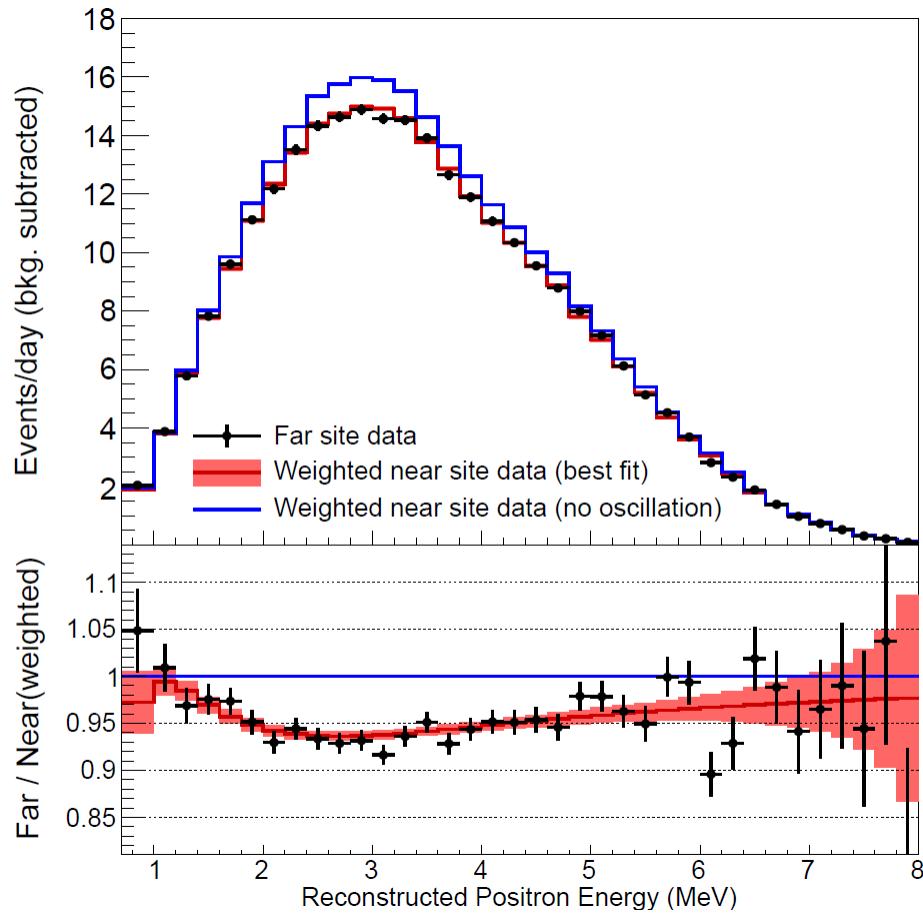


Oscillation Observed





Oscillation Analysis



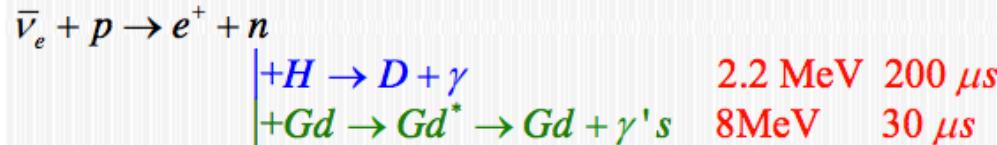
arXiv:1505.03456

$$\sin^2 2\theta_{13} = 0.084 \pm 0.005$$

$$|\Delta m_{ee}^2| = (2.42 \pm 0.11) \times 10^{-3} \text{ eV}^2$$



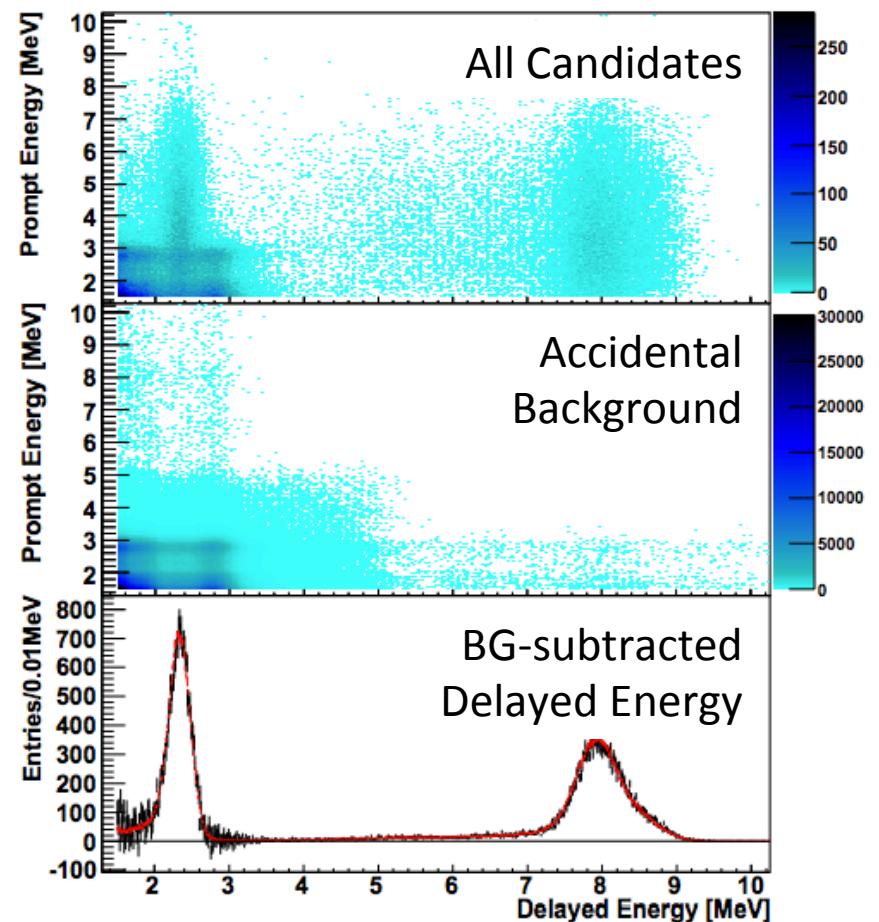
Oscillation Analysis using nH



PRD.90.071101

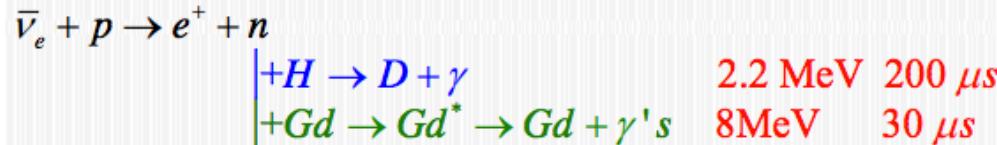
- Key features:** independent statistics, different systematics
- Challenges:** high accidental background because of longer capture time and lower delayed energy
- Strategy:** raise prompt energy cut ($>1.5\text{MeV}$) and require prompt to delay distance cut ($<0.5\text{m}$)
- Oscillation analysis** of rate deficit using 217 days of “6-AD” data

$$\sin^2 2\theta_{13} = 0.083 \pm 0.018$$





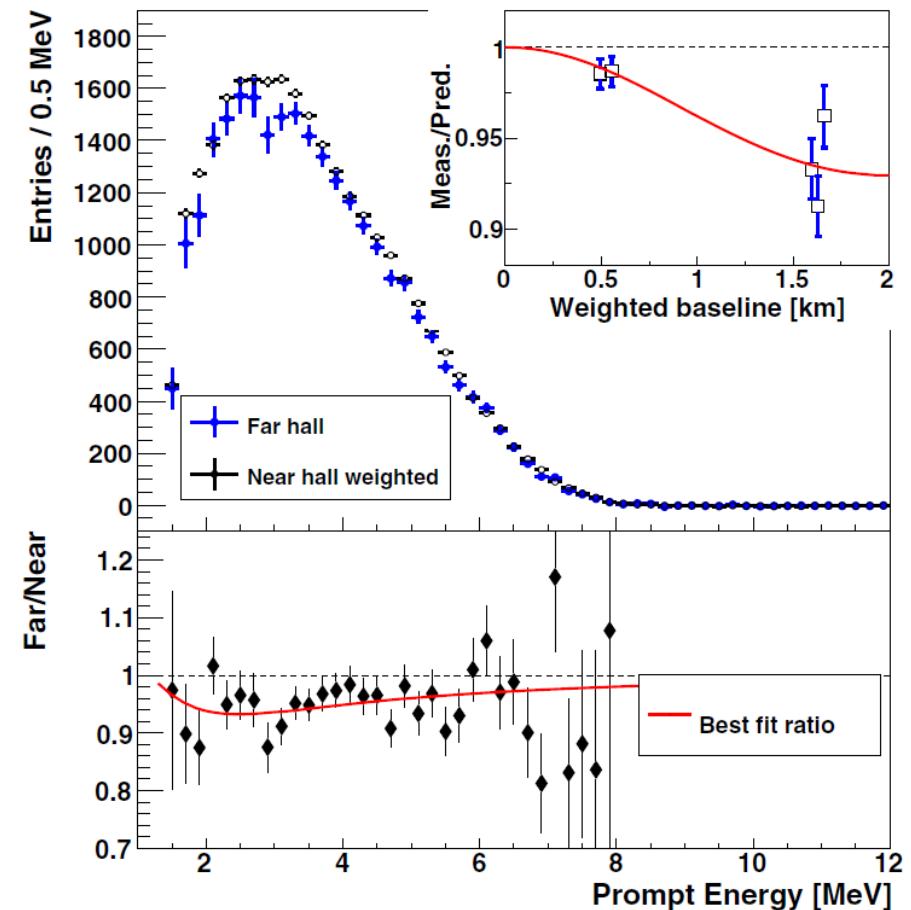
Oscillation Analysis using nH



PRD.90.071101

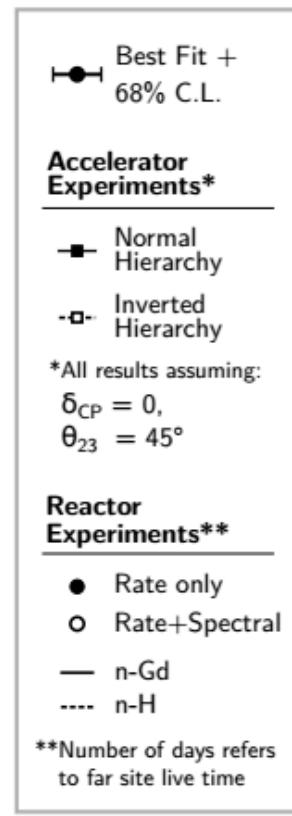
- Key features:** independent statistics, different systematics
- Challenges:** high accidental background because of longer capture time and lower delayed energy
- Strategy:** raise prompt energy cut ($>1.5\text{MeV}$) and require prompt to delay distance cut ($<0.5\text{m}$)
- Oscillation analysis** of rate deficit using 217 days of “6-AD” data

$$\sin^2 2\theta_{13} = 0.083 \pm 0.018$$

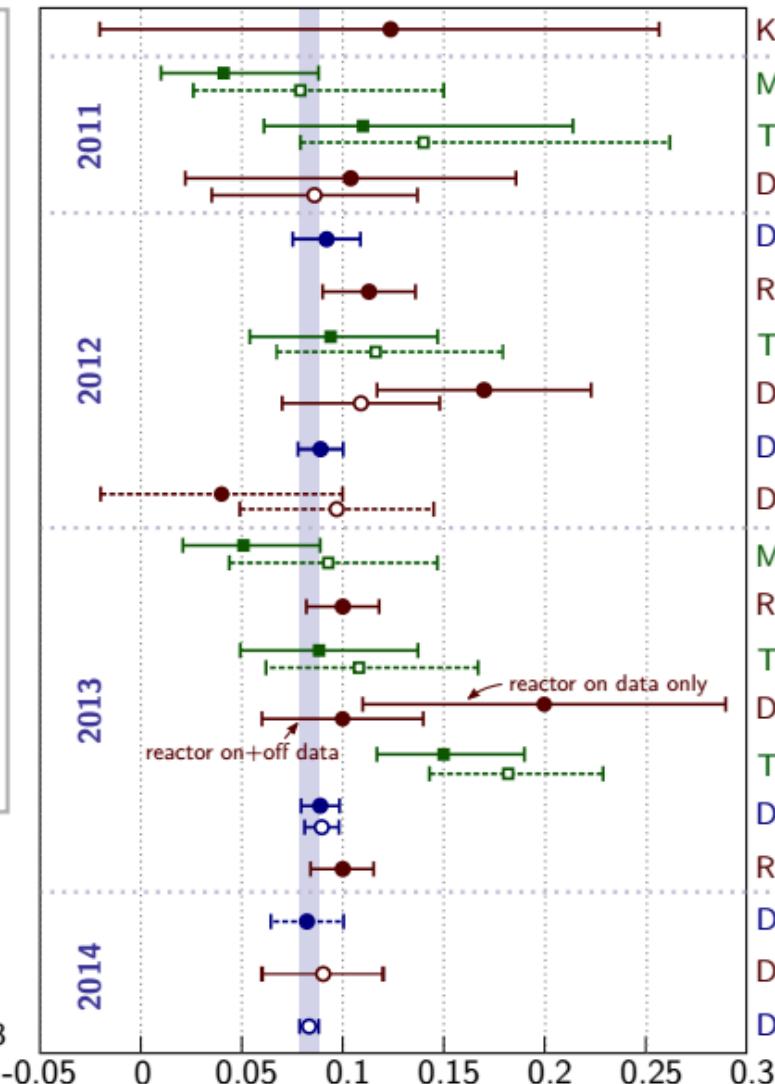




$\sin^2(2\theta_{13})$: Global Results



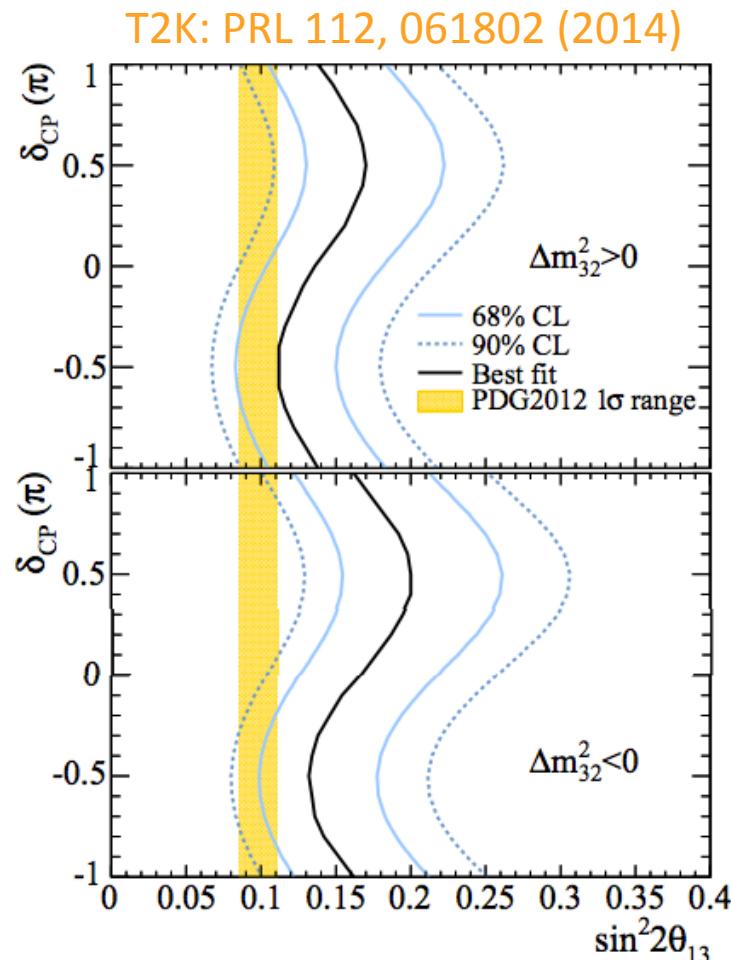
$\sin^2 2\theta_{13}$



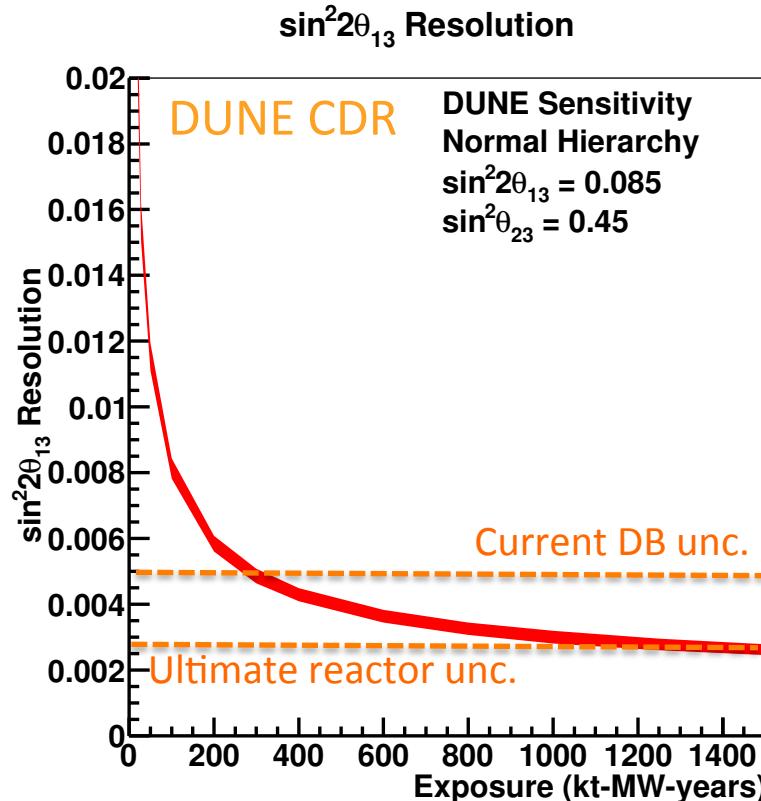
KamLAND	[1009.4771]
MINOS 8.2×10^{20} PoT	[1108.0015]
T2K 1.43×10^{20} PoT	[1106.2822]
DC 97 Days	[1112.6353]
Daya Bay 49 Days	[1203.1669]
RENO 222 Days	[1204.0626]
T2K 3.01×10^{20} PoT	[ICHEP2012]
DC 228 Days	[1207.6632]
Daya Bay 139 Days	[1210.6327]
DC n-H Analysis	[1301.2948]
MINOS 13.9×10^{20} PoT	[1301.4581]
RENO 403 Days	[NuTel2013]
T2K 3.01×10^{20} PoT	[1304.0841]
DC RRM Analysis	[1305.2734]
T2K 6.57×10^{20} PoT	[1311.4750]
Daya Bay 190 Days	[1310.6732]
RENO 403 Days	[TAUP2013]
Daya Bay 190 Days n-H	[Moriond2014]
DC 469 Days	[Neutrino2014]
Daya Bay 563 Days	[Neutrino2014]



Complementarity with Accelerator Experiments



Constraint on $\sin^2 \theta_{13}$ combined with T2K observation of ν_e appearance to give "hint" of δ_{CP} .

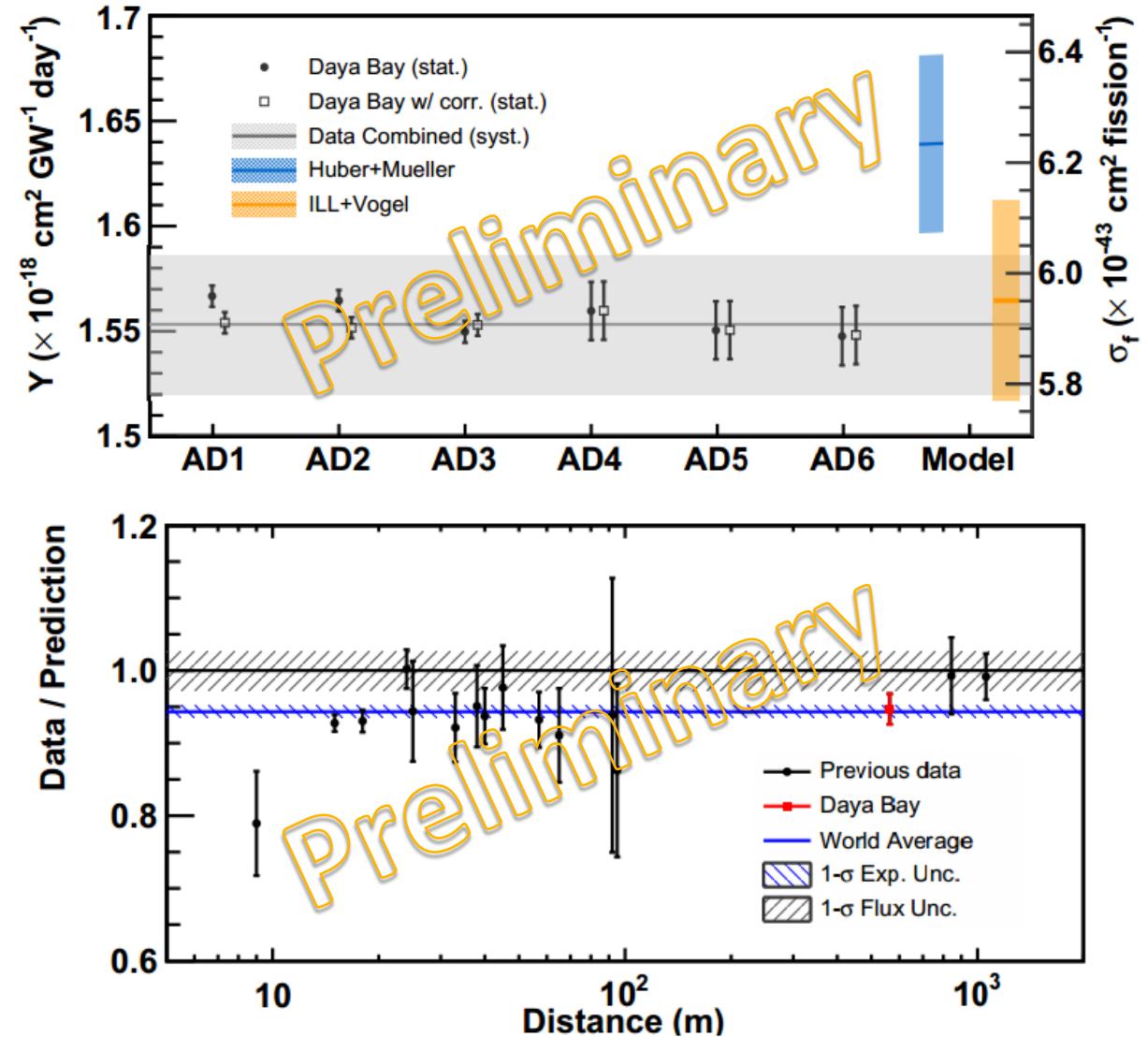


DUNE measurement of $\sin^2 2\theta_{13}$ expected to be comparable to that from reactor experiments → test of unitarity.

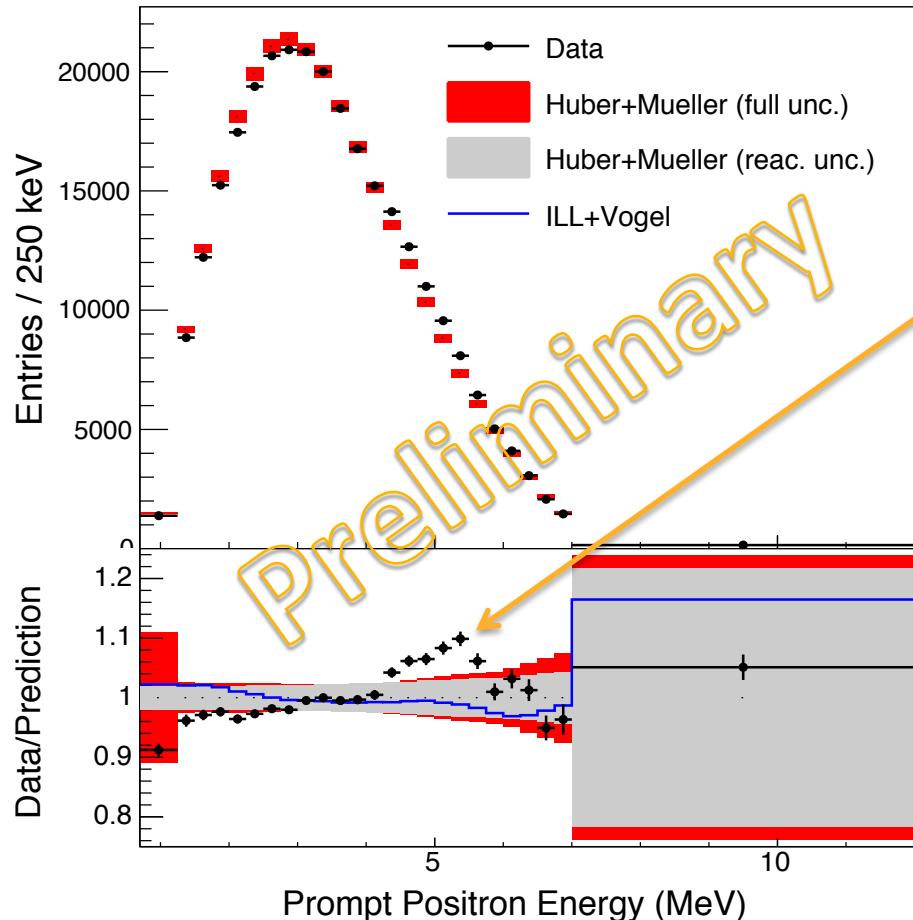
Reactor Antineutrino Flux

- Based on “6-AD” dataset
- Effective fission fractions:

^{235}U	^{238}U	^{239}Pu	^{241}Pu
0.586	.076	.288	.050
- “Reactor Anomaly”
 - Mention et al. (2011)
 - Zhang et al. (2013)
 - Measured antineutrino flux from reactors is lower than predicted
 - DB result consistent with previous short-baseline experiments



Reactor Antineutrino Spectrum

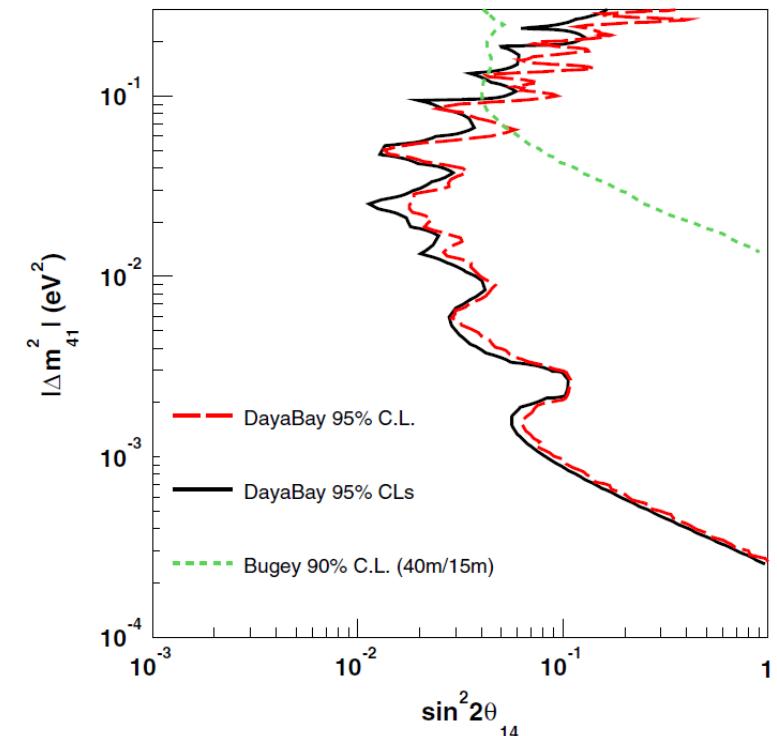
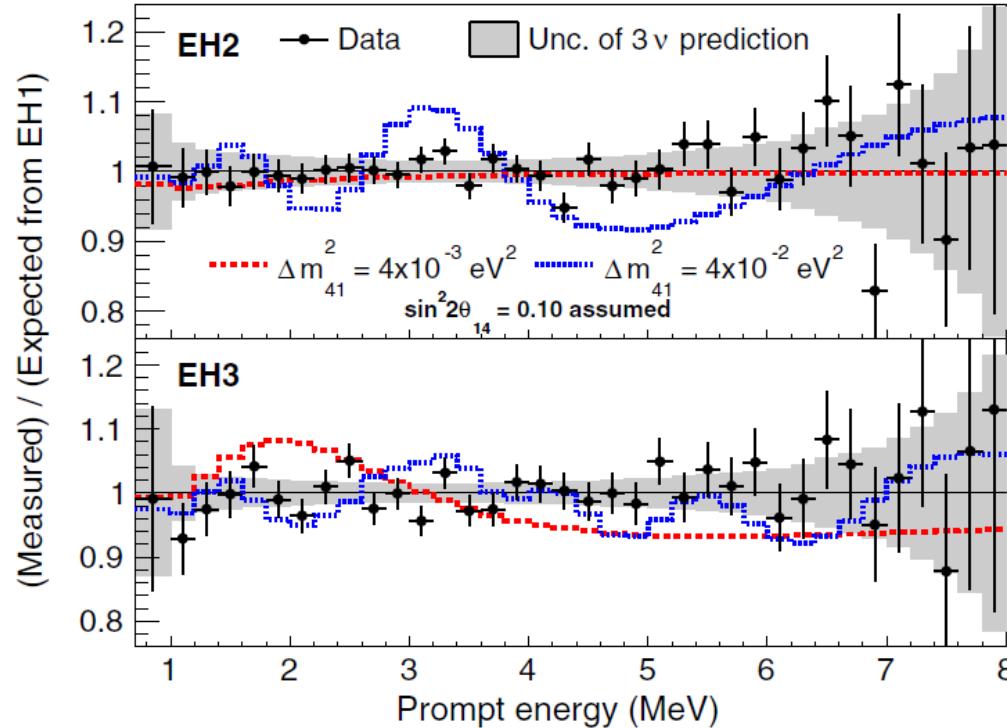


- Measured reactor antineutrino spectrum not consistent with prediction
 - Excess observed for positron energies of 4-6 MeV ($\sim 4\sigma$)
 - Similar feature reported by Double-Chooz and RENO
- Discrepancy possibly due to uncertainties in predicting expected ν spectra from measured β spectra
 - Dwyer, Langford, PRL 114, 012502 (2015)
 - Hayes et al., arXiv: 1506.00583

Search for Light Sterile Neutrino

- Sterile neutrino could introduce a new oscillation mode
- Relative measurement at multiple baselines
- Data (“6 AD”) is consistent with 3-flavor neutrino oscillation
- Most stringent limit: $10^{-3} \text{ eV}^2 < \Delta m_{41}^2 < 0.1 \text{ eV}^2$

PRL.113.141802





Summary of Daya Bay Results



- Measurement of $\sin^2 2\theta_{13}$ and $|\Delta m^2_{ee}|$ based on > 1 million neutrino interactions & using the full experimental configuration
 - $\sin^2 2\theta_{13} = 0.084 \pm 0.005$
 - $|\Delta m^2_{ee}| = (2.42 \pm 0.11) \times 10^{-3} \text{ eV}^2$
- Independent measurement of $\sin^2 2\theta_{13}$ using nH data
 - Consistent with nGd result
- Measurement of reactor antineutrino flux and spectrum
 - Flux consistent with previous short-baseline experiments
 - Spectrum has excess relative to prediction in 4-6 MeV region
- Limit on light sterile neutrino for $10^{-3} \text{ eV}^2 < \Delta m^2_{41} < 0.1 \text{ eV}^2$
 - PRL.113.141802
- Additional new physics searches in progress
- Daya Bay will continue collecting data through 2017

arXiv:1505.03456

PRD.90.071101